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DOCUMENT-IDENTIFIER: US 5742163 A
TITLE: Magnetic resonance scan calibration and reconstruction technique for multi-shot, multi-echo imaging

ABPL:
A sequence control (40) causes a transmitter (24) and gradient amplifiers (20) to transmit radio frequency excitation and other pulses to induce magnetic resonance in selected dipoles and cause the magnetic resonance to be focused into a series of echoes in each of a plurality of data collection intervals following each excitation. A receiver (38) converts each echo into a data line. Calibration data lines having a close to zero phase-encoding are collected during each of the data collection intervals. The calibration data lines in each data collection interval are zero-filled (86) to generate a complete data set and Fourier transformed (88) into a series of low resolution complex images (90.sub.1, 90.sub.2, . . . 90.sub.n), each corresponding to one of the data collection intervals. The low resolution images are normalized (92) and their complex conjugates taken (94). Imaging data lines are sorted by a data collection interval and zero-filled (104) to create full data sets. The full data set corresponding to each data sampling interval is Fourier transformed into partial image representations (106.sub.1, 106.sub.2, 106.sub.n). Each partial image is multiplied (108) by a complex conjugate of the normalized phase correction map (96) to create corrected partial images which are summed (112) to generate a composite image (114). The composite images are density corrected (120).

BSPR:
The present invention relates to the magnetic resonance arts. It finds particular application in conjunction with echo planar imaging (EPI) and will be described with particular reference thereto. However, it is to be appreciated that the present technique is also applicable to other rapid imaging sequences with repeated gradient echoes, spin echoes, or combinations of gradient and spin echoes, such as echo volume imaging (EVI) techniques, fast spin echo (FSE) techniques, and gradient and spin echo (GSE) techniques.

BSPR:
Heretofore, magnetic resonance imaging subjects have been positioned in a temporally constant magnetic field such that selected dipoles preferentially align with the magnetic field. A radio frequency pulse is applied to cause the preferentially aligned dipoles to resonate and emit magnetic resonance signals of a characteristic resonance radio frequency. The radio frequency magnetic resonance signals from the resonating dipoles are read out for reconstruction into an image representation.

BSPR:
In a two-dimensional Fourier transform imaging technique, a read gradient is applied during the read out of the echo for frequency encoding along a read axis and a phase-encode gradient is pulsed to step phase-encoding along a phase-encode axis between echoes. In this manner, each echo generates a data line in k-space. The relative phase-encoding of the data lines controls their relative position in k-space. Conventionally, the data line with zero phase-encoding extends across the center of k-space. Data lines with a phase-encoding gradient stepped in progressively positive steps are generally depicted as being above the center line of k-space; and, data lines with progressively negative phase-encoding steps are depicted as being below the center line of k-space. In this manner, a matrix, such as a 256.times.256 or a 512.times.512, etc., matrix of data values in k-space is generated. Fourier transformation of these values generates a

conventional magnetic resonance image.

BSPR:
To strengthen the received magnetic resonance signals, the initial signal is commonly refocused into an echo. This may be done by reversing the polarity of a magnetic field gradient to induce a field or gradient echo. Analogously, the radio frequency excitation pulse may be followed with a 180.degree. pulse to refocus the signal as a spin echo. Moreover, by repeating the reversing of the magnetic field gradient, a series of gradient echoes can be generated following each radio frequency excitation pulse. Analogously, a series of spin echoes can be generated following each radio frequency excitation pulse by repeating the 180.degree. radio frequency refocusing pulse. As yet another option, a single radio frequency excitation pulse can be followed by a mixture of spin and gradient echoes. See, for example U.S. Pat. No. 4,833,408 of Holland, et al.

BSPR:
In a single shot echo planar imaging (EPI) sequence using a gradient system which has a slew rate on the order of 20 mT/m/ms and a gradient strength 15 mT/m, a single radio frequency excitation pulse of arbitrary tip angle can be followed by a sufficient number of gradient reversals to generate an entire set of data lines. The magnetic resonance data from the object is collected during a series of echoes with an oscillatory read gradient that encodes the image object in the direction of the field gradient. See, e.g., P. Mansfield, J. Phys. Chemistry, Vol. 10, pp. L55-L58 (1977). In addition, a series of phase-encoding gradient pulses orthogonal to the read gradient direction are applied before each echo to step the data lines through k-space. The image of the object is preferably obtained with two one-dimensional Fourier transforms of the echo data. This single shot EPI technique offers an ultra fast imaging technique for true dynamic imaging in a sub-second time scale.

BSPR:
In accordance with the present invention, there is provided an apparatus and method for magnetic resonance imaging. A two-dimensional phase-correction processor generates a plurality of two-dimensional phase-correction matrices. The two-dimensional phase-correction processor receives data lines generated from echoes and independently generates a corresponding two-dimensional phase-correction matrix for each of a plurality of data collection intervals. A partial image processor receives image data and reconstructs an incomplete set of data lines collected during a data collection interval into a corresponding partial image. A matrix multiplier multiplies each partial image by the two-dimensional phase-correction matrix corresponding to the same data collection interval to generate a plurality of two-dimensionally phase-corrected partial images. An image adder adds the two-dimensionally phase-corrected partial images to generate a composite image.

DRPR:
FIGS. 1A and 1B taken together are a diagrammatic illustration of a magnetic resonance imaging system in accordance with the present invention;

DRPR:
FIG. 7 illustrates a preferred fast spin echo (FSE) sequence; and,

DEPR:
With reference to FIG. 1A, a main magnetic field control 10 controls superconducting or resistive magnets 12 such that a substantially uniform, temporally constant magnetic field is created along a z-axis through an examination region 14. A magnetic resonance echo means applies a series of radio frequency (RF) and magnetic field gradient pulses to invert or excite magnetic spins, induce magnetic resonance, refocus magnetic resonance, manipulate magnetic resonance, spatially and otherwise encode the magnetic resonance, saturate spins, and the like in order to generate magnetic resonance imaging and spectroscopy sequences. More specifically, gradient pulse amplifiers 20 apply current pulses to selected ones or pairs of whole body gradient coils 22 to create magnetic field gradients along x, y, and z-axes of the examination region 14. A digital radio frequency transmitter 24 transmits radio frequency pulses or pulse packets to a whole body RF coil 26 to transmit RF pulses into the examination region. A typical radio frequency pulse is composed of a packet of immediately contiguous pulse segments of short duration which taken together with each other and any applied gradients achieve a selected magnetic resonance manipulation. The RF

pulses are used to saturate spins, excite resonance, invert magnetization, refocus resonance, or manipulate resonance in selected portions of the examination region. For whole body applications, the resonance signals are commonly picked up by the whole body RF coil 26.

DEPR:
For generating images of limited regions of the subject, local coils are commonly placed contiguous to the selected region. For example, an insertable head coil 30 is inserted surrounding a selected brain region at the isocenter of the bore. The insertable head coil 30 preferably includes local gradient coils 32 which receive current pulses from the gradient amplifiers 20 to create magnetic field gradients along x, y, and z-axes in the examination region within the head coil 30. A local radio frequency coil 34 is used to excite magnetic resonance and receive magnetic resonance signals emanating from the patient's head. Alternatively, a receive-only local radio frequency coil can be used to receive resonance signals induced by body-coil RF transmissions. An RF screen 36 blocks the RF signals from the RF head coil from inducing eddy currents in the gradient coils and the surrounding structures. The resultant radio frequency signals are picked-up by the whole body RF coil 26, the local RF coil 34, or other specialized RF coils and demodulated by a receiver 38.

DEPR:
A sequence control circuit 40 controls the gradient pulse amplifiers 20 and the transmitter 24 to generate any of a plurality of multiple echo sequences, including echo-planar imaging, echo-volume imaging, gradient and spin echo imaging, fast spin echo imaging, and the like. For the selected sequence, the receiver 38 receives a plurality of data lines in rapid succession following each RF excitation pulse. Preferably, the receiver 38 is a digital receiver or, as shown here, is accompanied by an analog-to-digital converter 42 for converting each data line into a digital format.

DEPR:
With reference to FIG. 6, other driven equilibrium sequences are also contemplated. In FIG. 6, like elements with FIG. 2 are denoted with the same reference numeral, but followed by a prime ('). For example, an .alpha..degree. excitation pulse 52' is followed by a 180.degree. inversion pulse 190. The timing of the gradient echoes 58', 60' is adjusted relative to the 180.degree. refocusing pulse and the excitation pulse such that one of the generated echoes, 62.sub.s ' is a spin echo and the remainder are gradient echoes. One or more additional 180.degree. pulses are applied to refocus the resonance into subsequent spin echoes.

DEPR:
Referring generally to FIGS. 2 and 3, in order to describe the principles of the invention more clearly, consider the case of a two-dimensional magnetic resonance image with multiple echoes. After the slice selection excitation 52, the resultant magnetic resonance magnetization induction signal of a three-dimensional object with proton spin density .rho.(x,y) is given by: ##EQU1## where q denotes the echo number, k.sub.rd (t) and k.sub.pe (t) are the k-space trajectory of read-out and phase-encoding gradients, respectively: ##EQU2## where G.sub.rd and G.sub.pe are the time dependent magnetic field read out and phase-encoding gradients during acquisition, and .DELTA..phi.(x,y) denotes a phase error due to main field inhomogeneity which includes the contribution of both magnet main field and susceptibility. The transverse spin relaxation is taken into account by the term involving T.sub.2. Gradient eddy current field effect is not included in this expression for simplicity of calculation.

CLPR:
1. In a magnetic resonance imaging system which includes a magnet for generating a temporally constant magnetic field through an examination region, a radio frequency pulse controller and transmitter for inducing dipoles in the examination region to resonance such that radio frequency resonance signals are generated, gradient magnetic field coils and a gradient magnetic field controller for generating at least phase and read magnetic field gradient pulses in orthogonal directions across the examination region and for repeatedly reversing the read gradient, a receiver for receiving and demodulating the radio frequency magnetic resonance signals after each reversal of the read gradient to produce a series of data lines, and an image memory for storing a reconstructed image

representation, the improvement comprising:

CLPR:
2. In the magnetic resonance imaging system as set forth in claim 1, the improvement further comprising the two-dimensional phase-correction processor including:

CLPR:
3. In the magnetic resonance imaging system as set forth in claim 2, the improvement further comprising:

CLPR:
4. In the magnetic resonance imaging system as set forth in claim 3, the improvement further comprising:

CLPR:
5. In the magnetic resonance imaging system as set forth in claim 1, the improvement further comprising:

CLPR:
6. In the magnetic resonance imaging system as set forth in claim 1, the improvement further comprising:

CLPR:
7. In the magnetic resonance imaging system as set forth in claim 6, the improvement further comprising:

CLPR:
8. In the magnetic resonance imaging system as set forth in claim 1, the improvement further comprising:

CLPR:
9. In a method of magnetic resonance imaging in which magnetic resonance is excited in dipoles which are induced to form echoes at each of a plurality of data collection intervals following each resonance excitation, the echoes being read out along a read axis in the presence of a read gradient to form a series of data lines for reconstruction into an output image representation, the improvement comprising the steps of:

CLPR:
14. A method for magnetic resonance imaging comprising:

CLPV:
refocusing magnetic resonance signals to generate echoes;